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AN ANALYSIS OF AIRCRAFT REQUIREMENTS TO MEET UNITED STATES DEPARTMENT OF AGRICULTURE REMOTE SENSING GOALS

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Abstract

The survey needs of the U.S. Department of Agriculture are immense, ranging from individual crop coverage at specific intervals to general land use classification. The aggregate of all desirable resolutions and sensor types applicable to airborne platforms yields an annual survey coverage rate equivalent to about 6 times the U.S. land area. An intermediate annual survey level equal to the U.S. area can meet all currently perceived crop survey needs and provide sample imagery over many other resource areas. This decreased survey level can be accomplished with one or two high altitude aircraft (e.g., U-2 or WB-57) or medium altitude aircraft (such as the Learjet or Jetstar). Survey costs range from about 25 cents to several dollars per square nautical mile depending primarily on resolution requirements and the aircraft used.

Introduction

This is a summary of work done for the United States Department of Agriculture (USDA) as part of a cooperative project with the National Aeronautics and Space Administration (NASA). Although considerable time was involved in establishing groundrules and requirements, the numbers presented in this paper do not necessarily represent complete or official statements of

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goals or recommendations by either participant and no such inference should be made.

The analysis involves the combined evaluation of observation tasks, sensors, and aircraft platforms. Specific consideration was also given to the data handling requirements. The survey requirements are treated in two ways: in terms of specific resource type (area, resolution, and frequency) as indicated by the USDA, and also in terms of blanket U.S. coverage. Sensors examined are exclusively camera systems, although scanners are recognized as a possible future option. Aircraft of different altitude capability are examined, and tradeoffs between altitude, image size, swath width, resolution, coverage rate, and cost are indicated.

Due to the variety of remote sensing techniques available (including satellite and ground-based data collection platforms, as well as aircraft), and considering the large diversity of agricultural and non-agricultural surveys undertaken by the USDA, it was not possible to identify any single best approach to aircraft surveys. Consequently, what is presented here is largely a parametric tool that will aid knowledgeable decisions as requirements and constraints are established.

Summary

This report presents the results of a study of airborne platform remote sensing capability considered in terms of USDA requirements and in the context of possible alternative means of meeting such data needs. The analysis was based extensively on similar NASA-Ames studies of earth resource observations that were previously completed using U-2's. Additional effort went toward matching the analysis to USDA observation requirements, as well as to including information on other aircraft types, other possible sensors, and data handling. Because observation requirements cannot be stated with absolute certainty and aircraft program characteristics can only be estimates at best, analytical results are described parametrically. Some general conclusions can be drawn, however, and they are offered below.

The foremost conclusion is that standard configuration, commercially available high altitude (~40,000-45,000 ft) jet aircraft probably offer the best compromise in aerial coverage rate, payload flexibility, and cost with reasonable resultant image

resolutions. The viability of high altitude jet aircraft (i.e., U-2 or B-57) depends almost entirely on aircraft availability. If one or more U-2's were to be made available from the military at no cost, it is possible that they could be operated in a manner that would be competitive with the Learjet-class platform. Although the U-2 is more expensive to operate, its higher altitude offers a greater coverage rate capability. Analysis shows that lower altitude aircraft (~5000-15,000 ft) are cheaper to operate on an hourly basis, and even on a linear mile basis, but the additional miles flown and additional images needed to cover a given area can result in an overall higher cost.

One interesting possibility was revealed in the form of a small turboprop aircraft produced by E-Systems of LTV which is capable of long endurance at altitudes above 40,000 ft in a manned or remotely piloted configuration. The apparent low operating cost of the manned version warrants further investigation of availability and cost. The remotely piloted version is not as attractive, partly because of cost and partly because of operational constraints, such as the limited operational radius of about 200 n.mi. due to line of sight (LOS) operations. The Compass Cope remotely piloted vehicle (RPV) has a higher operational altitude but suffers from the same disadvantages as above: small operational radius, high operational cost, availability only in prototype form, and political problems of operation over populated areas.

Because resolution requirements vary significantly from task to task, optimum sensor (or camera) selection generally falls into two categories. For high resolution data needs a long focal length lens is desired. In this case the best performance is achieved by a panoramic camera which not only produces good resolution, due to its 24-in. lens, but yields an unparalleled swath width by scanning 100 to 120° across the aircraft flight line. In many cases it is more convenient to handle the images from a 3.5- or 6-in. focal lens on a 9×9-in. format camera. The ground area per image is then about 10 and 3-1/2 times the area of the panoramic image, respectively, while using well under one-half the film area. However, while the panoramic camera may produce resolutions from less than a foot to a few feet, the 6-in. lens might yield resolutions from several feet to 25 ft, and the 3.5-in. lens would resolve perhaps 20 to 50 ft. Ignoring resolution requirements, the 3.5-in. lens system is significantly less costly to operate, the cost being as low as about $\$0.15/\text{n.mi.}^2$ on the E-Systems vehicle. The 6-in. lens system on a Lear-type

aircraft resulted in a total cost of about \$0.30/n.mi.^{2}. And the panoramic camera on the Learjet resulted in a cost of about \$0.60/n.mi.^{2}.

USDA Survey Requirements

The survey needs of the USDA are immense, ranging from individual crop coverage at specific intervals, to general land use classification. The requirements are, in fact, so diverse, that they can be treated in two ways, first as a function of individual resources, or second, as a conglomerate blanket coverage. The magnitude of the uniform coverage would presumably bear some relationship to the sum of the rates of the individual resource coverage requirements.

In order to establish a perspective for the coverage requirement analysis, recent USDA aircraft survey practices were reviewed. It was found that most of the aerial photographic missions were flown at low altitudes — typically between 10,000 and 15,000 ft, and that most of the data (about 85%) were collected on 9-in. black and white film with a 6-in. focal length lens. In FY 1973 the total aerial survey contracted value was \$891,000 for 208,000 n.mi.^{2}. The average cost of imagery was over \$4/n.mi.^{2}. Depending on film type, altitude focal length, and other factors, this cost has varied from about \$2 to over \$13/n.mi.^{2} since 1964. A histogram of the quantity of area photographed as a function of altitude and focal length is shown in Fig. 1; note that the typical resolution is 1 to 2 m.

The USDA aircraft survey program currently runs about \$2 million for aircraft-associated costs and \$6-million for data processing and handling, excluding data transformation costs (map making, etc.). About one-tenth of the U.S. land area is surveyed each year.

A more ambitious aircraft program is desired in order to meet the growing survey needs. These needs have been expressed by USDA personnel in the form of a comprehensive computer listing. For each resource category there are specifications of observation frequency, sensor or film type, and resolution. A condensation of coverage requirements has been made and is shown in Fig. 2. Frequency of coverage requirements are shown as a function of resolution for each major resource category. All requirements of similar resolution have been combined regardless of film type specified. Also, resolution requirements greater than 10 m are

excluded and assumed to be best satisfied by satellite. Note that certain of the larger resolution requirements could be satisfied by flights intended to collect high resolution data, if the coverage time tolerances overlap. These potentially redundant coverages are indicated by values shown in parentheses.

The total equivalent nonredundant annual area coverage is 12.9 billion acres (15.2 million square nautical miles) or 5.6 times the U.S. land area. This coverage represents an upper limit in the sense that it does not consider the very real possibility of sampling in the large forest, range, and wildland areas. The crop growing areas constitute only 1.28 billion acres of equivalent coverage or about 0.6 times the U.S. area. (The actual crop land area is less than 20% of the area of the U.S.)

Other possible schemes or survey strategies involve various degrees of sampling. One such method would be to completely survey all crop areas and then do 10% of the remaining requirement by samples. The result is an equivalent annual coverage of 1.07 times the area of the U.S. A somewhat less ambitious project would be to cover the entire crop area, as specified, but then cover one-tenth of the remaining U.S. land area each year. This is 0.64 times the U.S. area. Note that in all these cases, the redundant coverage was eliminated; that is, the numbers in parentheses in Fig. 2 were not included.

Resolution requirements can have a significant impact on configuring an aircraft program. The validity of configuring and comparing aircraft programs on the basis of uniform or blanket U.S. coverage is a function of the degree to which data of one form can be substituted for another. To the extent that one resolution, or date of coverage, or film type can be substituted for another, or to the extent that cameras with different film types can be flown simultaneously, the blanket coverage approach is reasonable.

Airborne Survey Platforms

The aircraft available for airborne remote sensing have a wide range of altitude, speed, endurance, stability, and cost characteristics. With the growing availability of higher altitude platforms the economic benefit of more synoptic coverage can easily be demonstrated.

Two classes of high altitude aircraft are considered here, the commercially available aircraft and aircraft services operating at altitudes between 35,000 and 45,000 ft, and the still research oriented, albeit routinely operated, 60,000 to 70,000 ft altitude capability aircraft. The Learjet and Jetstar aircraft are in the first category. NASA's U-2 and B-57 aircraft fall into the second. The advantage of the higher altitude is primarily attributed to the fewer images required to depict a particular ground area. The cost of operation is invariably higher, however, at least on an hourly basis.

The general characteristics of the aircraft classes of primary analytical interest are shown in Fig. 3; assumed costs are shown in Fig. 4. The performance parameters of first order concern are altitude (which is one determinant of instantaneous field of view and resolution), cruise velocity (which partly determines area covered per unit of time), and cost of operation (which helps determine cost per unit area of coverage). Of second order importance is aircraft range (which has an influence on base requirements and aircraft utilization efficiency). Payload weight potential is not considered per se, since the platforms examined have sufficient capability to handle the camera and film needed for most requirements. This point should be examined further, however, should it be necessary to simulanteously gather data at several resolutions or on several types of film.

Flight Efficiency

One important aircraft operating parameter is flight efficiency. The flight efficiency is defined as the ratio of data taking hours (or miles) to total flown hours (or miles). A flight efficiency of 40%, for example, means that 40% of the aircraft air time is available for picture taking over desired territory. Conversely, it could be stated that the flight time theoretically required for data gathering must be multiplied by 250% (i.e., 1/40%) to obtain an estimate of actual flight time.

The actual flight efficiency (or time) is difficult to predict because it depends on actual resource location, base location relative to the resource, shuttle or ferry flights between bases, cloud interference, sun angle constraints (or other factors which limit flight duration), flight planning, and pilot proficiency. Theoretical flight efficiency values approach unity under ideal conditions (e.g., coverage of a narrow strip of land stretching away from a base which allows full coverage with a trip out and

back). Theoretical flight efficiency values under more general circumstances have been calculated to be between 40% and 60%. Actual flight efficiencies in research specialized, or non-routine situations average between 20% and 25% and have run even less. A typical low efficiency operation would be one in which a deployed aircraft had to spend most of its flight time getting to and from a survey site near the periphery of its flight radius.

For lack of a better number until actual survey conditions can be specified, a flight efficiency of 40% is suggested. This number is based on the kind of expected coverage depicted in the lower right of Fig. 5.

Aircraft Utilization

The aircraft utilization rate — or number of hours flown per aircraft per year — affects survey requirements and costs because it has a direct effect on the number of aircraft required. Utilization rates vary greatly for different aircraft applications. At the very most, the utilization could be 24 hr a day or 8760 hr a year, less the time on the ground for refueling, inspection, cleaning, maintenance, bad weather, pilot illness, etc. Commercial airlines take advantage of a high utilization rate, approaching 4000 hr per year. For earth resource surveys, sunlight is a normal requirement. Flying would frequently be practical for only one or perhaps two flights per day. In this case the utilization would be between 500 and 1500 hr per year. Practical considerations (i.e., maintenance, flight scheduling, sensor changing, etc.) decreases the upper limit to about 1000 hr per year. One thousand hours per year has been selected for this study as a middle ground between the high commercial utilization rates and the low domestic and experimental utilization rates.

A word of caution about using or drawing conclusions about any of the aircraft data, especially costs: although there is a reasonable degree of confidence that can be applied to the data presented, there is always an element of uncertainty. It is virtually impossible to apply generalizations or rules of thumb to aircraft characteristics without a full knowledge of all parameters governing the situation of operation. The cost numbers are particularly suspect where the availability of the aircraft is uncertain or the size of the fleet to be employed is not established. Basing strategies, cloud criteria, sun angle constraints, coverage flexibility, and a host of other parameters can strongly affect operations and cost.

Sensor Systems

The sensor systems of primary interest in this study are film cameras. There are already many large format, high resolution camera systems available and in use. The camera systems currently available on the U-2 are listed in Fig. 6. Most commonly used is the RC-10 with a 6-in. focal length and 9×9-in. film. This is the same situation as with the USDA surveys, except that NASA most often uses color IR film while the USDA uses black and white panchromatic or black and white IR. Another camera system of particular interest is the panoramic which gives an extremely wide swath width and simultaneously delivers good resolution. The penalty paid for this performance is in film handling, since relatively few square miles are depicted on each 4.5×50-in. frame.

The ground coverage of a number of different camera systems is shown in Fig. 7. The imaged areas are fixed, relative to each other, but the total coverage changes with altitude as shown by the scales on the right. Resolution is primarily a function of altitude and lens focal length as shown in Fig. 8. Many other factors influence resolution, however, including atmospheric conditions, inherent lens performance, dirty windows, platform stability, film type, etc. The figure shows typical results, under normal situations. The tradeoff obviously becomes one of synoptic coverage achieved by shorter focal lengths and high resolution achieved by longer focal lengths. The economic consequences of this tradeoff are discussed in the following section.

The expense of film, film processing, and data archiving can be a significant, and even dominant, part of a total resource survey cost. In 1 hr of flying, for example, as many as 500 panoramic images could be clicked off from a high altitude jet aircraft. The costs associated with film processing and archiving are shown in Fig. 9. The total costs used in this study for film and handling are \$4.00, \$6.00, and \$8.00 for 9×9-in., 9×18-in., and panoramic images, respectively. It is assumed that one duplicate of each frame is made. Additional duplicates would, of course, add to the cost.

Aircraft/Sensor Combinations

A plot of individual aircraft coverage rate as a function of resolution is given in Fig. 10. Coverage rates of three candidate aircraft are plotted with five different camera systems.

Note that the greatest coverage is achieved by the U-2 with its superior altitude and high speed capability. The Learjet class of vehicle follows closely behind, while the slower E-Systems manned turboprop brings up the rear. It should be pointed out that all of these vehicles perform well relative to the more commonly used low altitude platforms. Because of its great swath width, the panoramic system covers more ground than the others, while collecting high resolution data at the same time.

The aircraft survey cost data is plotted in Fig. 11, showing the relative amount of aircraft and data (film) associated costs for a sampling of the aircraft and camera combinations analyzed. Each case is represented by a bar composed of a shaded portion to represent the aircraft cost and an open portion showing the film costs. Overall costs range from about $0.15/n.mi.^{2} to several dollars. In the panoramic systems the film costs are a major portion of the total cost. The same is true for the other long focal length cases. The cases that use the U-2 have substantial aircraft costs, but some compensation is gained by the altitude. Long focal lengths on the 9×9-in. film produce the highest costs. The lowest costs are obtained by using the short focal lengths on the same film size.

If the cost of doing aerial surveys, as calculated here, is compared with other data sources, some interesting but logical results are observed. First of all, the survey costs shown are generally less than the costs incurred in ongoing surveys. This should be expected because it is more cost effective to use higher altitude platforms for blanket area coverage; the speed is higher, the swath width is wider, and the images are fewer. It is even cheaper, however, to purchase imagery which has already been taken, such as from the USDI-EROS Data Center in Souix Falls. While a data-taking flight might result in survey costs from a few dollars per square nautical mile down to less than a dollar, the amortized print costs can be a few cents per square mile.

In order to make comparisons of platform/sensor combinations on a more equitable basis, an additional analysis was made for certain of the more compromising systems. The comparison was made by dividing the aircraft/camera systems into resolution capability classes. The low resolution class includes a 20,000-ft aircraft with a 3.5-in. lens, a Learjet with a 6-in. lens and a U-2 with an 8.25-in. lens. The U-2 with a 6-in. lens was also included since it is so commonly used. The high resolution cases include the Learjet and U-2 with panoramic cameras, and a 7000-ft-

altitude aircraft with a 6-in. focal length lens. For maximum comparability, some panoramic cameras were constrained to swath widths comparable to the corner to corner swath angle of the 6-in. lens on a 9-in. film format, but the full 120° panoramic swath cases were also included. Figure 12 shows how these nine options compare on the basis of resolution, aircraft requirements, aircraft cost, film cost, total cost, and cost per unit area. Where oblique viewing of ground objects is a problem (as is particularly the case in hilly areas) note should be taken of the field of view shown at the bottom of the diagram.

The total yearly program costs for the options compared in Fig. 12 are plotted in Fig. 13 as a function of resolution. Both diagrams assume a total equivalent annual coverage equal to the U.S. land area (i.e., 2.72 million square nautical miles). The conclusions that can be drawn from this comparison must, of course, depend on the exact survey requirements. It is possible, however, to state general recommendations. First, for example, it is easy to see that the conventional low altitude survey methods are noncompetitive with the high altitude platforms with panoramic cameras where high resolution is desired. For the high resolution requirement, the Learjet and U-2 are very competitive if it is assumed that the U-2 can be obtained essentially free of charge from the military. For low resolution coverage, the U-2 does not appear to be competitive with the Learjet or medium altitude platforms. As it would seem intuitively, low resolution coverage is cheaper than high resolution coverage, in this case by a factor of 2 or 3.

A more detailed cost summary for two typical examples is given in Fig. 14. The costing procedure includes estimates for sensor purchase and maintenance, film processing and data handling set up costs, and an additional allowance on the aircraft purchase price for all possible avionics. As before, all initial costs are amortized at a rate of 10% per year. Base costs, as before, are included in the aircraft costs. The resultant costs are somewhat higher than produced before because of the additional parameters included. The cost of $0.43/n.mi.^{2} for the low resolution case can be compared directly with the Learjet case at $0.27 in Fig. 11. The high resolution case, at $0.71/n.mi.^{2} can be compared with the $0.58 found in the first bar of Fig. 11. Note that the number of flight hours per year to cover the U.S. once each year in this example does not come out at a 1000 hr utilization rate. As is shown later, this is not a critical parameter. Note also, that although the high resolution

case requires only one aircraft while the low resolution case requires two, but the low resolution case is cheaper because much fewer images are required.

Since all of the preceding costs are predicated on a number of assumptions about aircraft performance, costs, data requirements, etc., it is appropriate to analyze the sensitivity of total survey cost to certain of these parameters. It can be shown for example, that total costs are very sensitive to changes in swath width. It may be necessary to change the swath width to achieve a different resolution. This could be done by changing the focal length of the lens or by changing the aircraft altitude. Some dramatic effects occur because the swath width not only changes the amount of flying that must be done, it also affects the number of images required to cover a given area. For example, halving the swath width doubles the required flight time and quadruples the number of images. Figure 15 shows how changes in a number of parameters affect the survey cost of a more or less typical system using a Learjet, a 6-in. lens on 9×9-in. film, a flight efficiency of 40%, a utilization rate of 1000 hr per year, a swath width of 12 n.mi., and a requirement for one film duplicate per frame. The figure should be used only one parameter at a time unless the changes are relatively small. The figure is used by first noting that the survey is about $0.27/n.mi.^{2}, given the baseline parameters. The consequence of changing any particular parameter on one of the horizontal scales is found by following the curve above with the same letter symbol as the scale. To illustrate, a change from an aircraft utilization rate of 1000 hr per year to 500 hr per year (scale B), results in a change in the survey cost from $0.27/n.mi.^{2} to about $0.35/n.mi.^{2} (curve B). Utilization rate is not a sensitive parameter due to the fact that aircraft utilization rate does not affect the number of images produced or change the direct flight costs (fuel, pilot, etc.).

Although most systems were referred to by name, no recommendation of any system or company is intended. There are many aircraft, for example, that are capable of cruising above 40,000 ft. It would be a mistake to conclude that any one was better suited for agricultural surveys than another without further investigation of performance and cost when applied to an exact set of area and resolution requirements. All cost numbers are suspect until such time as the necessary contracts are negotiated. Despite cost uncertainty, it does not appear that remotely piloted vehicles can compete with manned vehicles. First of all, the ground crew is

larger than a typical flight crew (and hence is more expensive), the risk of loss is higher, and the operational radius is restricted to about 200 n.mi. because of line of sight radar. And finally, there remains a problem of public acceptance of pilotless vehicles in populated areas and air spaces.

Data Handling Considerations

In the preceding portion of this report, certain basic film and processing functions were assumed; namely, that the film would be developed, a duplicate made, and the film archived. These assumptions are embodied in the kind of system that is in operation at NASA-Ames and Johnson Space Center. Basically, everything is there to help the user find the imagery he needs. An alternative system is used by the USGS-EROS Data Center at Sioux Falls.

Data interpretation or transformation costs can be higher than the data acquisition costs. Experience shows that analysis and ground truth can run upwards of several hundred dollars per square nautical mile. Mapping can cost several dollars or more per square mile. Any aircraft survey program should be configured with full cognizance of the effect of interpretation and transformation costs.

For certain applications (e.g., where thermal data is desired), scanners on aircraft might be very attractive. Generally speaking, such scanners do not have good resolution relative to film systems, although high resolution scanners are feasible. Unfortunately, the electro-mechanical nature of a scanner requires that a great deal of data be generated and processed if any substantial area is to be viewed with good resolution. It was found in a previous analysis of a Landsat-type scanner aboard a U-2 that substantially greater aircraft and data processing costs would be encountered by scanners than by film systems where, say, 3-m resolution was required. Not only is the cost of computer processing the digital data high (potentially several thousands of dollars per image), but the imaging swath width is greatly reduced if resolutions comparable to the photographic systems are to be maintained. Keep in mind, however, that the photographic data must still be interpreted or transformed, while the scanner data might be interpreted for only a small additional charge.

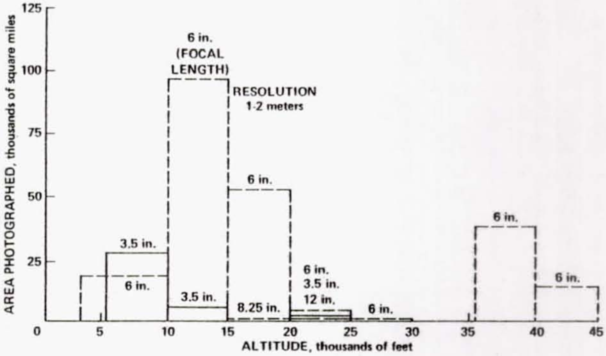

Figure. 1. USDA aerial photography histogram (1973).

RESOURCE	AREA 10^6 acres	RESOLUTION, m									TOTAL 10^6 acres
		0.1	.3	.5	1	2	3	5	8	10	
CORN FOR GRAINS	57					4			(1)		228 (57)
WHEAT	47	1$^{\oplus}$				4			(1)	(1)	188 (132)
OATS	19					4	(4)		(4)		76 (152)
SUGAR BEETS	1.4					4					5.6
RICE, ROUGH	1.8				1	(4)^3			(1)		7.2 (1.8)
SORGHUMS FOR GRAINS	14					4				(10)^6	140 (56)
COTTON & SEED (EXCEPT LINTERS)	13				1	(4)^3					52
HAY	63					4	(1)				252 (63)
SOYBEANS	42					4					168
IRISH POTATOES	1.3					4	(4)				5.2 (5.2)
TOBACCO	0.8					4			(4)		3.2 (3.2)
OTHER CROPS	31		1			(1)			(1)		31 (62)
SUMMER FALLOW, IDLE	92						1				92
FARMSTEADS, ROADS, LANES	8		4*				(4+)				32 (32)
GRAZED CROPLAND, GRASSLAND, PASTURE, RANGE	692		4*				(10)^6				6920 (2768)
GRAZED FOREST	198		4	(1)							792 (198)
UNGRAZED FOREST	525		4	(1)							2100 (525)
RURAL PARKS AND WILDLIFE REFUGE	81		4				(4+)				324 (324)
URBAN, TRANSPORTATION & INDUSTRIAL	65						4+				260
NATIONAL DEFENSE (18) FED FLOOD CONTROL, NAVIG. RECLAMATION, IRRIGATION	33		4	(1**)	(1**)		(1**)				132 (99)
WILDLANDS, SNOWFIELD, DESERT, SWAMP, TUNDRA, ETC.	279		4		(1†)		(1)	(1)			1116 (837)
TOTAL	2,264										12924 (58152)

*ANIMAL SURVEYS
+LAND USE PLANNING
**SEVERE EROSION AREAS
( ) THEORETICALLY REDUNDANT
†1.5m IN SNOW, WATER, FLOOD AREAS
$\oplus$ WINTER WHEAT ONLY

Figure 2. Resource coverage requirements.

AIRCRAFT	ALTITUDE, ft	SPEED, knots	SERVICE RADIUS n. mi.
U-2	60-70,000	400	1200
CESSNA CITATION	25-41,000	325-345	600
LEARJET 24E	41-45,000	418-464	600
SABRE 60	31-45,000	430-489	700
E-SYSTEMS L-450F (MANNED)	40-43,000	220	800
E-SYSTEMS L-450F RPV	40-43,000	220	200
COMPASS COPE	55,000	320	200

Figure 3. Aircraft candidates.

AIRCRAFT	U-2	CESSNA CITATION	LEARJET 24E	SABRE 60	E-SYSTEMS MANNED	E-SYSTEMS RPV	COMPASS COPE RPV
INITIAL COSTS ($)	9M	0.9M	0.9M	1.7M	0.5M	0.9M	7M
FIXED OP. COSTS ($/yr)	650K	90K	56K	80K	25K	110K	1M
VARIABLE OP. COST ($/hr)	1300	200	240	300	50	300	1800
AMORTIZATION ($/yr)	900K	90K	90K	170K	50K	90K	700K
TOTAL COST	3M	380K	386K	550K	125K	500K	3.5M

Figure 4. Aircraft performance and cost assumptions.

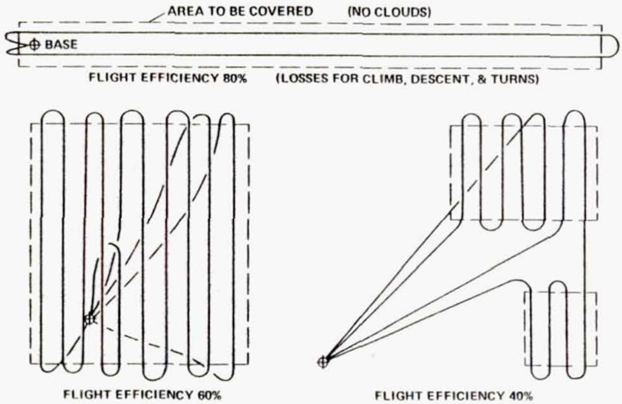

Figure 5. Flight efficiency.

DESIGNATION	LENS	FILM FORMAT, in.	GROUND COVERAGE @ 65,000 ft	NOMINAL RESOLUTION @ 65,000 ft
VINTEN (FOUR)	1-3/4 in. F.L. F 2.8	2-1/4 x 2-3/16	14 x 14 n. mi. (EACH)	10 – 20 m
I²S MULTISPECTRAL (FOUR BANDS) K-22	100 mm F.L. F 2.8	9 x 9 (4 @ 3.5)	9 x 9 n. mi.	6 – 10 m
RC-10	6 in., F 4	9 x 9	16 x 16 n. mi.	3 – 8 m
RC-10	12 in., F 5.6	9 x 9	8 x 8 n. mi.	1.5 – 4 m
HR-732	24 in., F 8	9 x 18	4 x 8 n. mi.	0.6 – 3 m
WIDE ANGLE	3.5 in.	9 x 9	27 x 27 n mi.	6 – 25 m
ITEK PANORAMIC	24 in.	4.5 x 50	2 x 37 n. mi.	0.3 – 2 m

Figure 6. Camera systems.

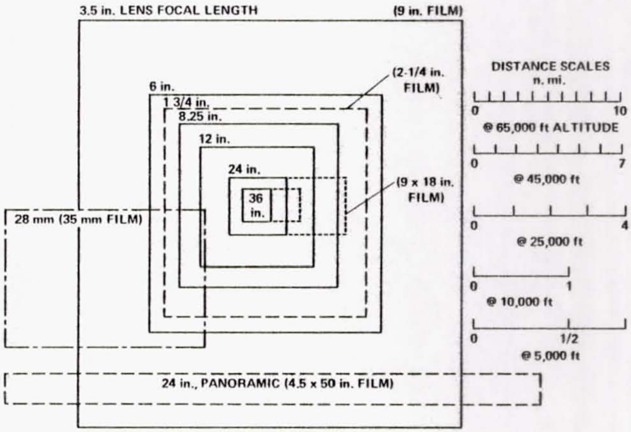

Figure 7. Relative camera coverage.

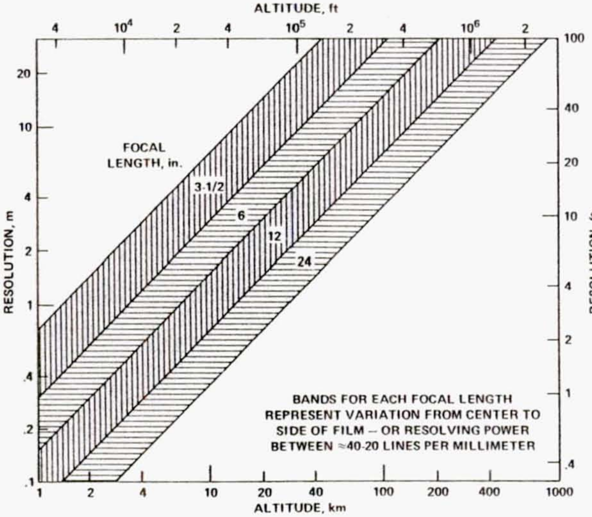

Figure 8. Lens resolution.

FORWARD OVERLAP OF PICTURES: 50%
SIDE OVERLAP: NEGLIGIBLE
FILM TYPE: COLOR INFRARED

ITEM/FUNCTION	FILM SIZE		
	9 x 9 in.	9 x 18 in.	4.5 x 50 in.
FILM AREA/IMAGE	81 in.^{2}	162 in.^{2}	225 in.^{2}
ORIGINAL FILM COST	1.00	2.00	2.50
PROCESSING COST	1.00	1.25	1.50
DUPLICATE COST (ONE)	1.00	1.50	2.00
ARCHIVING COST	1.00	1.25	2.00
TOTAL COST/IMAGE	$4.00	$6.00	$8.00

Figure 9. Data handling cost assumptions.

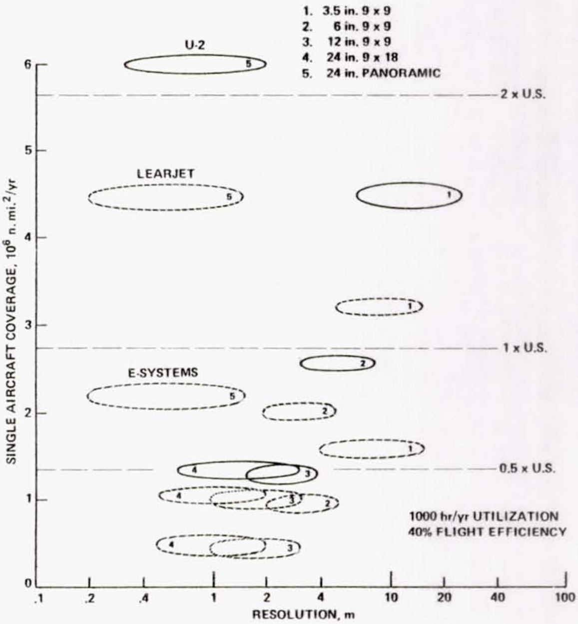

Figure 10. Coverage vs resolution.

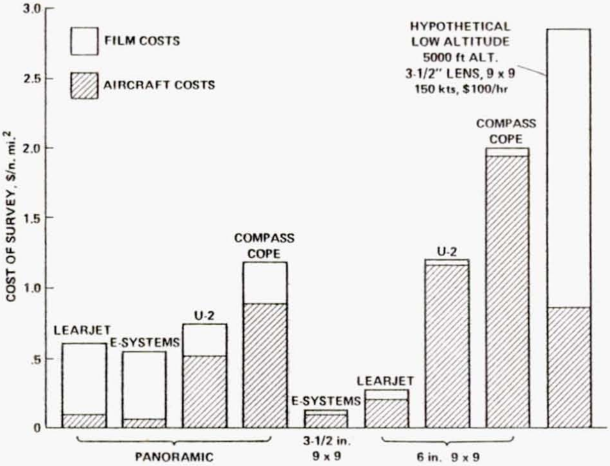

Figure 11. Typical aircraft survey cost comparison.

	LOW RESOLUTION				HIGH RESOLUTION				
AIRCRAFT	MED ALT**	U-2	LEAR	U-2	U-2	LEAR	U-2	LEAR	LOW ALT***
SENSOR (F.L., FILM)	3-1/2 in. 9 x 9	8-1/4 in. 9 x 9	6 in. 9 x 9	6 in. 9 x 9	24 in. pan	24 in. pan	24 in. pan	24 in. pan	6 in. 9 x 9
RESOLUTION (m)	2-7	2-5	2-5	3-8	0.3-2	0.2-1.5	0.3-1	0.2-0.7	0.3-0.8
SWATH (n. mi.)	8.5	11.7	10.6	16	37	24.5	22.6	15	1.72
SWATH 10% O.L. (n. mi.)	7.6	10.5	9.5	14.4	33.3	22	20.3	13.5	1.55
A/C VELOCITY (n. mi./hr)	200	400	425	400	400	425	400	425	150
COVERAGE RATE (n. mi.²/hr)	1520	4200	4050	5760	13,300	9360	8120	5720	232
COV. RATE 40% EFF (n. mi.²/hr)	609	1680	1620	2300	5330	3745	3248	2288	93
FLIGHT TIME - 1 x U.S. (hr)	4465	1620	1680	1180	510	726	837	1190	29,250
A/C COST RATE (\$/hr)	200	2000	400	2000	2000	400	2000	400	150
A/C COST - 1 x U.S.*	\$893K	\$3.24M	\$672K	\$2.36M	\$1.02M	\$290K	\$1.67M	\$476K	\$4.39M
# AIRCRAFT REQUIRED	≈5	2	2	1-2	1	1	1	1-2	≈30
AREA/IMAGE- 50% O.L. (n. mi.²)	36	68	56	128	37	16	22.6	9.9	1.48
IMAGES/1 x U.S.	76,000	40,000	48,600	21,250	73,500	168,000	120,400	275,000	1,840,000
TOTAL IMAGE COST	\$304K	\$160K	\$194K	\$85K	\$588K	\$1.34M	\$963K	\$2.2M	\$7.35M
TOTAL PROGRAM COST	\$1.20M	\$3.4M	\$866K	\$2.45M	\$1.61M	\$1.63M	\$2.63M	\$2.68M	\$11.74M
COST RATE (\$/n. mi.²)	0.44	1.25	0.32	0.90	0.59	0.80	0.97	0.98	4.32
	120° FOV CORNER TO CORNER	75° TO CORNERS	93° FOV CORNER TO CORNER		120° FOV		RESTRICTED SWATH; 93° FOV MATCHES 6 in., 9 x 9 CORNER TO CORNER		93° TO CORNERS

*U-2 PURCHASE PRICE NOT INCLUDED
**20,000 ft
***7,000 ft

Figure 12. Primary option comparisons (1 × U.S.).

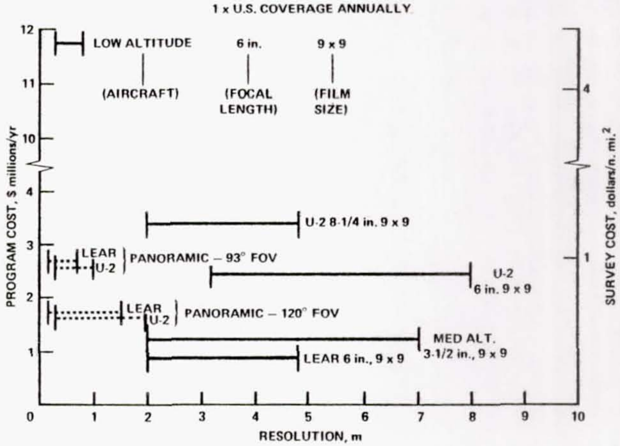

Figure 13. Survey option cost vs resolution.

	HIGH RESOLUTION	LOWER RESOLUTION
AIRCRAFT SENSOR RESOLUTION	MED. ALT. JET 24 in. PANORAMIC 0.2 – 1.5 m	MED. ALT. JET 6 in. LENS, 9 x 9 in. 2 – 5 m
NO. A/C REQ. FLIGHT HRS. REQ.	1 600	2 1400
A/C PURCHASE $ CAMERA COST $ BASE SET UP $* DATA SET UP $ TOTAL SET UP $	1.5M 200K —— 1M 2.7M	3.0M 100K —— 600K 3.7M
AMORTIZED INIT. $ A/C OPERATION $ CAMERA MAINT $ BASE OPS. $* DATA PROC. $	270K 200K 110K —— 1,350K	370K 450K 140K —— 200K
TOTAL ANNUAL $ $/n. mi.^{2}	1,930K .71	1,160K .43

*INCLUDED IN AIRCRAFT OPERATIONS

Figure 14. Typical requirement summary.

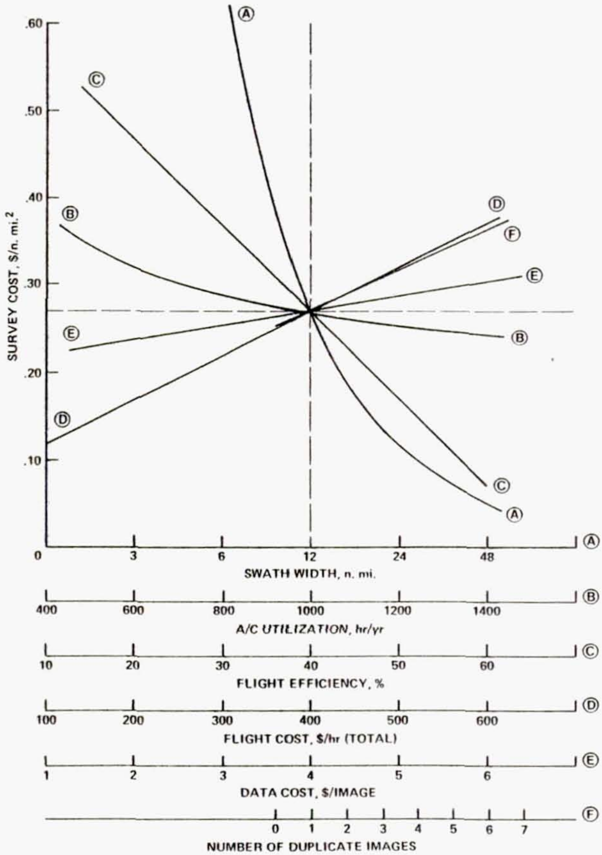

Figure 15. Aircraft survey parameter sensitivity.